

Reheating Temperature and Inflaton Mass Bounds from Thermalization After Inflation

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Abstract

We consider the conditions for the decay products of perturbative inflaton decay to thermalize. The importance of considering the full spectrum of inflaton decay products in the thermalization process is emphasized. It is shown that the delay between the end of inflaton decay and thermalization allows the thermal gravitino upper bound on the reheating temperature to be raised from 10^8 GeV to as much as 10^{12} GeV in realistic inflation models. Requiring that thermalization occurs before nucleosynthesis imposes an upper bound on the inflaton mass as a function of the reheating temperature, $m_S \lesssim 10^{10}(T_R/1 \text{ GeV})^{7/9}$ GeV. It is also shown that even in realistic inflation models with relatively large reheating temperatures, it is non-trivial to have thermalization before the electroweak phase transition temperature. Therefore the thermal history of the Universe is very sensitive to details of the inflation model.

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1 Introduction

Reheating is a fundamental process in early Universe cosmology [1], in which the energy density in a coherently oscillating inflaton field is converted to thermalized relativistic particles. Originally it was believed that this occurred simply by the perturbative decay of the individual scalar particles in the corresponding Bose condensate of inflatons [1, 2], but in recent times it has become clear that the process can be considerably more complicated, with non-perturbative processes such as parametric resonance [3] and quantum creation of fermions [4, 5] playing a significant role. Nevertheless, in many models, even if there is an early stage of preheating, the latter stage of reheating is dominated by the perturbative decay of the remaining inflaton energy density. An important issue is then the thermalization of the inflaton decay products. Since the inflaton can be a very massive particle, as heavy as 10^{15} GeV in some typical inflation models [6, 7], it is not obvious that its highly energetic decay products will thermalize rapidly. In this paper we will consider the conditions under which complete thermalization of the inflaton decay products occurs. We will see that the results are particularly important in SUSY inflation models, allowing the thermal gravitino upper bound on the reheating temperature [8, 9] to be substantially increased. In addition, we will show that thermalization can occur at low temperatures even in realistic inflation models, as low as the electroweak phase transition temperature or less. We will also calculate the upper bounds on the inflaton mass following from the requirement of thermalization before nucleosynthesis [1, 9].

2 Thermalization of Inflaton Decay Products

There are two distinct processes involved in thermalization of the decay products, which we shall refer to as "self-thermalization" and "catalysed thermalization".

In order to avoid confusion, we first define what we mean by the "thermalization temperature" and the "reheating temperature". We will define radiation as a background of relativistic particles. The thermalization temperature, T_{th} , refers to the temperature of the radiation when the relativistic particles can scatter rapidly enough

relative to the expansion rate of the Universe to come into thermal equilibrium. The reheating temperature, T_R , is defined as the temperature the radiation *would* have at the time when the Universe becomes radiation dominated *if* it were in thermal equilibrium. This is the conventional reheating temperature of inflation models, which usually assume that thermalization of the inflaton decay products is instantaneous.

(i) Self-Thermalization

The energy density of the decaying inflaton field, S , is given by

$$\rho_S = \left(\frac{a_o}{a}\right)^3 \rho_{So} e^{-\Gamma_d t}, \quad (1)$$

where a is the scale factor and Γ_d is the inflaton decay rate. Thus most of the energy density in the inflaton field decays when $H \approx \Gamma_d$ (where $H = 2/3t$ is the expansion rate during inflaton matter domination), just before the Universe becomes dominated by relativistic particles. Therefore the apparent condition for the inflaton decay products to thermalize is that these decay products should thermalize by scattering from each other. We refer to this process, the thermalization of decay products produced during an interval $\delta t \approx H^{-1}$ by scattering from each other, as self-thermalization. However, we will see later that this condition for the thermalization of the radiation background is incorrect; there are also much lower energy particles in the spectrum of decay products, coming from the red-shifted decay products of earlier inflaton decays, which play a crucial role in the thermalization process.

We first derive an upper bound on the inflaton mass from self-thermalization of the decay products produced during $\delta t \approx H^{-1}$ at the end of inflaton decay. The initial energy of the decay products will be of the order of the inflaton mass, m_S . The condition for the thermalization of these decay products by scattering from each other is then

$$\Delta n(H) \sigma_{sc}(H) \gtrsim H. \quad (2)$$

Here Δn is the number of decay products at H which were produced in a time $\delta t \approx H_R^{-1}$ at H_R , where H_R is the expansion rate when the Universe becomes radiation dominated. This is given by

$$\Delta n(H) \approx \left(\frac{a_{H_R}}{a_H}\right)^3 \Gamma_d H_R^{-1} n_S, \quad (3)$$

where $n_S \approx \rho_S(H_R)/m_S$ is the number of inflatons remaining in the condensate at H_R , a_H is the scale factor at H and Γ_d is the inflaton decay rate, given by

$$\Gamma_d = \frac{k_{TR} T_R^2}{M_{Pl}} ; \quad k_T = \left(\frac{4\pi^3 g(T)}{45} \right)^{1/2} , \quad (4)$$

where T_R is the conventional reheating temperature and $g(T)$ is the number of relativistic degrees of freedom. The scattering rate at H for relativistic particles of initial energy $E \approx m_S$ at H_R is given by

$$\sigma_{sc} \approx \frac{\alpha^2}{E^2} \approx \left(\frac{a}{a_R} \right)^2 \frac{\alpha^2}{m_S^2} , \quad (5)$$

where $\alpha = g^2/4\pi$ corresponds to the gauge or Yukawa couplings. (For now we will consider massless decay products.) Thus the condition for complete self-thermalization at a temperature $T < T_R$ is

$$m_S \lesssim \left(\frac{T_R}{T} \right)^{1/3} \left(\frac{3M_{Pl} k_T \alpha^2}{8\pi} \right)^{1/3} T_R^{2/3} \equiv m_{self} . \quad (6)$$

Numerically we find

$$m_{self} = 2.9 \times 10^7 \alpha^{2/3} \left(\frac{1 \text{ MeV}}{T} \right)^{1/3} \left(\frac{T_R}{1 \text{ GeV}} \right) \text{ GeV} , \quad (7)$$

where we have used $k_T \approx 17$ ($g(T) \approx 100$).

(ii) Catalysed Thermalization

The naive approach to thermalization considers only the self-thermalization of the decay products produced at the end of reheating. In fact, there will also be red-shifted decay products from earlier inflaton decays. If these have red-shifted sufficiently, their scattering rate ($\propto E^{-2}$) can become large and so they can self-thermalize, transferring their energy density from a small number of high energy particles to a larger number of low energy particles. These can then act as targets for higher energy particles in the energy spectrum to scatter from and thermalize, with the process continuing until all the decay products are thermalized. We refer to this process as "catalysed thermalization". The conditions for catalysed thermalization to occur are then that (i) there are particles in the energy spectrum of decay products of sufficiently low energy

as to be able to self-thermalize and so provide a "seed" for catalysed thermalization and (ii) that catalysed thermalization can then thermalize the whole spectrum of decay products in a time $\lesssim H^{-1}$.

In order to discuss catalysed thermalization, we need the spectrum of decay products, $dn(E, T)/dE$, at T . Inflaton decay during a time $\delta t_i \approx H_i^{-1}$ at H_i contributes a number density at H given by

$$dn(H, H_i) \approx \left(\frac{a_{H_i}}{a_H}\right)^3 \Gamma_d H_i^{-1} \frac{\rho_S(H_i)}{m_S} . \quad (8)$$

The energy of the decay products red-shifts to

$$E = \left(\frac{a_{H_i}}{a_H}\right) m_S \equiv \left(\frac{H_R}{H_i}\right)^{2/3} \left(\frac{H}{H_R}\right)^{1/2} m_S , \quad (9)$$

for $H < H_R$. In the following, it will be sufficient to consider the spectrum at $H < H_R$, since the tightest bounds generally correspond to both the largest red-shift of the decay products and the smallest value of H . Thus we find

$$dn(H, H_i) = \left(\frac{T}{T_R}\right)^{3/2} \frac{\rho_S(H_R)}{m_S} \left(\frac{E}{m_S}\right)^{3/2} . \quad (10)$$

The change in energy at H of the decay products produced at H_i in a time $\delta t_i \approx H_i^{-1}$ is $\delta E \approx -2E/3$. Thus

$$\frac{dn}{dE} \approx -\frac{3}{2} \left(\frac{T}{T_R}\right)^{3/2} \frac{\rho_S(H_R)}{m_S} \frac{E^{1/2}}{m_S^{3/2}} , \quad (11)$$

for $H < H_R$. An important point in what follows is that this spectrum has a low energy cut-off, at E_{min} , corresponding to the inflaton decay products produced at the earliest time, immediately after the end of inflation at $H = H_I$,

$$E_{min} = \left(\frac{H_R}{H_I}\right)^{2/3} \left(\frac{H}{H_R}\right)^{1/2} m_S \equiv \left(\frac{T}{T_R}\right) \left(\frac{k_{T_R} T_R^2}{M_{Pl} H_I}\right)^{2/3} m_S . \quad (12)$$

The condition for a self-thermalized seed to exist at $H < H_R$ is then that, for some energy $E_c > E_{min}$, self-thermalization of the decay products can occur for all E up to E_c ,

$$\frac{dn}{dE} \frac{\alpha^2}{E} \gtrsim H , \quad \forall E \lesssim E_c . \quad (13)$$

Using Eq. (11), we find that E_c is given by

$$E_c = \frac{9\pi g(T_R)\alpha^4 M_{Pl}^2 T_R^5}{320 m_S^5 T} . \quad (14)$$

A self-thermalized seed will therefore exist if E_{min} is less than E_c at the smallest value of T , which imposes an upper bound on the inflaton mass

$$m_S \lesssim \left(\frac{T_R}{T}\right)^{1/3} \left(\frac{9\pi g(T_R) M_{Pl}^8 \alpha^4}{320 k_{T_R}^{2/3}}\right)^{1/6} T_R^{4/9} H_I^{1/9} \equiv m_{seed} , \quad (15)$$

where $T < T_R$. Numerically we find

$$m_{seed} = 8.8 \times 10^{10} \alpha^{2/3} \left(\frac{T_R}{1 \text{ GeV}}\right)^{7/9} \left(\frac{1 \text{ MeV}}{T}\right)^{1/3} \left(\frac{H_I}{10^{13} \text{ GeV}}\right)^{1/9} \text{ GeV} . \quad (16)$$

If this is satisfied, then catalysed thermalization can thermalize the spectrum up to some energy E_{cat} such that, for all $E \leq E_{cat}$,

$$\left(\frac{dn}{dE} E^2\right)^{3/4} \frac{\alpha^2}{E^2} > H . \quad (17)$$

In this we have taken the number density of thermalized particles to be $\approx \rho_E^{3/4}$, where $\rho_E \approx E dn/dE$ is the energy density in particles of energy E to $2E$. E_{cat} is then given by

$$E_{cat} = \left(\frac{9}{16\pi}\right)^6 \frac{\alpha^{16} k_{T_R}^4 M_{Pl}^8 T_R^8}{m_S^{15}} \left(\frac{T_R}{T}\right)^7 . \quad (18)$$

In order to thermalize the whole spectrum we then require that $E_{cat} \geq E_{max}$, where $E_{max} = (T/T_R)m_S$, which imposes the upper bound,

$$m_S \lesssim \left(\frac{T_R}{T}\right)^{1/2} \left(\frac{3}{8\pi}\right)^{3/8} \alpha M_{Pl}^{1/2} k_{T_R}^{1/4} T_R^{1/2} \equiv m_{cat} . \quad (19)$$

Numerically we find

$$m_{cat} \approx 1.0 \times 10^{11} \alpha \left(\frac{T_R}{1 \text{ GeV}}\right) \left(\frac{1 \text{ MeV}}{T}\right)^{1/2} \text{ GeV} . \quad (20)$$

Since both of these upper bounds must be satisfied in order to have catalysed thermalization, the complete upper bound from catalysed thermalization can be stated

as $m_S \lesssim \text{Min}(m_{seed}, m_{cat})$. The upper bounds from catalysed thermalization are considerably weaker than the naive upper bound based on self-thermalization, Eq. (7), typically by two to three orders of magnitude.

If $m_S > \text{Min}(m_{seed}, m_{cat})$ at T , then catalysed thermalization will be incomplete. In particular, if $m_S > m_{seed}$ then there will be no catalysed thermalization. If $m_{seed} < m_S < m_{cat}$ then there will be a degree of thermalization, up to E_c in the spectrum, but most of the energy will remain unthermalized; the thermalized energy density, corresponding to $\rho_S(E \leq E_c)$, is proportional to m_S^{-40} , so the suppression of the thermalized component for $m_S > m_{cat}$ will be extremely large.

3 Consequences for Thermal Gravitinos, Nucleosynthesis and the Electroweak Transition

So far we have not considered a specific inflation model, so our results are valid for both SUSY and non-SUSY models. In general, there is a lower bound on the thermalization temperature from nucleosynthesis, $T_{th} \gtrsim 1$ MeV [9]. In addition, in SUSY inflation models there is an upper bound from requiring that gravitinos are not produced thermally, $T_{th} \lesssim 10^{8-9}$ GeV for gravitino masses in the range 100–500 GeV [8, 9]. Usually it is assumed that the inflaton decay products thermalize instantaneously, so that T_{th} is identified with T_R . However, this depends on the inflaton mass. Perhaps the most interesting consequence of this is that the thermal gravitino upper bound on T_R can be considerably relaxed in realistic SUSY inflation models. To see this, we note that thermal gravitinos can only be generated at $T \lesssim T_{th}$. Thus the thermal gravitino upper bound should be $T_{th} \lesssim 10^{8-9}$ GeV. If $m_S \gtrsim \text{Min}(m_{seed}, m_{cat})$ when $T \approx 10^{8-9}$ GeV, then thermalization will occur safely below the thermal gravitino upper bound for the corresponding value of T_R . In Table 1 we give values of m_{seed} and m_{cat} as a function of T_R for the case $T = 10^8$ GeV. (The values of m_{seed} and m_{cat} for $T = 10^9$ GeV are given by multiplying the values in Table 1 by 0.46 and 0.32 respectively.) From this we see that for inflaton masses in the range 10^{15-16} GeV, as would be expected, for

example, in D-term inflation models¹, the upper bound on the reheating temperature T_R is 10^{10-12} GeV. Given the importance of the thermal gravitino upper bound as a constraint on inflation models, this weakening of the upper bound on T_R is significant.

Table 1. Inflaton Mass Lower Bounds from Thermal Gravitino Non-production.

T_R	$m_{seed}/(\alpha^{2/3} \left(\frac{H_I}{10^{13} \text{ GeV}}\right)^{1/9})$	m_{cat}/α
10^8 GeV	$3.2 \times 10^{13} \text{ GeV}$	$3.2 \times 10^{13} \text{ GeV}$
10^9 GeV	$1.9 \times 10^{14} \text{ GeV}$	$3.2 \times 10^{14} \text{ GeV}$
10^{10} GeV	$1.1 \times 10^{15} \text{ GeV}$	$3.2 \times 10^{15} \text{ GeV}$
10^{11} GeV	$6.9 \times 10^{15} \text{ GeV}$	$3.2 \times 10^{16} \text{ GeV}$
10^{12} GeV	$4.1 \times 10^{16} \text{ GeV}$	$3.2 \times 10^{17} \text{ GeV}$
10^{13} GeV	$2.5 \times 10^{17} \text{ GeV}$	$3.2 \times 10^{18} \text{ GeV}$
10^{14} GeV	$1.5 \times 10^{18} \text{ GeV}$	$3.2 \times 10^{19} \text{ GeV}$
10^{15} GeV	$8.9 \times 10^{18} \text{ GeV}$	$3.2 \times 10^{20} \text{ GeV}$

The nucleosynthesis lower bound on T_{th} imposes upper bounds on the inflaton mass. These bounds are relatively weak for large T_R , but for smaller values of T_R they can be significant. In the context of SUSY models there have been some recent motivations for considering low reheating temperatures. One is from Affleck-Dine baryogenesis [11, 12, 13]. For the lowest dimension R-parity conserving flat directions of the MSSM scalar potential, those with dimension $d = 4$ and 6 (where the dimension refers to the non-renormalizable superpotential terms responsible for lifting the flat directions [12, 13, 14]), the observed baryon asymmetry requires that the reheating temperature is approximately 10^7 GeV and 1 GeV respectively [13, 14]. So $T_R \approx 1$ GeV is one favoured possibility if the baryon asymmetry originates via the Affleck-Dine mechanism. Another motivation for low reheating temperatures is the possibility that large non-thermal gravitino densities are created by the oscillating inflaton field

¹The inflaton mass in D-term inflation models is given by $m_S = \lambda \xi$, where λ is the Yukawa coupling of the inflation sector fields and the microwave background implies that $\xi \approx 7 \times 10^{15}$ GeV [6, 10]

at the end of inflation [5]. Although the resulting upper bound on the reheating temperature is sensitive to the details of the inflation model, there are indications that, for mass scales typical of inflation models, the upper bound is likely to be² $T_R \lesssim 10^3$ GeV [5].

Table 2. Inflaton Mass Upper Bounds vs. Thermalization Temperature

T_R	T_{th}	$m_{self}/\alpha^{2/3}$	$m_{seed}/(\alpha^{2/3} (\frac{H_I}{10^{13} \text{ GeV}})^{1/9})$	m_{cat}/α
1 GeV	1 MeV	2.9×10^7 GeV	9.2×10^{10} GeV	1.0×10^{11} GeV
1 GeV	1 GeV	2.9×10^6 GeV	9.2×10^9 GeV	1.0×10^{10} GeV
10^3 GeV	1 MeV	2.9×10^{10} GeV	2.0×10^{13} GeV	1.0×10^{14} GeV
10^3 GeV	10^2 GeV	6.3×10^8 GeV	4.3×10^{11} GeV	3.2×10^{11} GeV
10^3 GeV	10^3 GeV	2.9×10^8 GeV	2.0×10^{11} GeV	1.0×10^{11} GeV
10^8 GeV	1 MeV	2.9×10^{15} GeV	1.5×10^{17} GeV	1.0×10^{19} GeV
10^8 GeV	10^2 GeV	6.3×10^{13} GeV	3.2×10^{15} GeV	3.2×10^{16} GeV
10^8 GeV	10^8 GeV	6.3×10^{11} GeV	3.2×10^{13} GeV	3.2×10^{13} GeV

In Table 2 we give the upper bound on the inflaton mass as a function of the thermalization temperature for $T_R = 1$ GeV, 10^3 GeV, and 10^8 GeV. For $T_R \approx 1$ GeV the nucleosynthesis upper bound from catalysed thermalization implies that $m_S \lesssim 10^{10-11}$ GeV. Given that the inflaton mass scale in SUSY inflation models can naturally be $m_S \approx 10^{15-16}$ GeV, this can impose a significant constraint on inflation models compatible with $d = 6$ AD baryogenesis. We also give the upper bound for the case $T = T_R$, corresponding to the case where the inflaton decay products instantaneously thermalize. This requires that $m_S \lesssim 10^{9-10}$ GeV for $T_R \approx 1$ GeV. These bounds are much weaker than would be expected from naive self-thermalization; comparing m_{seed} with m_{self} shows that self-thermalization would impose an upper bound smaller by a factor of more than 10^3 . For the case $T_R \approx 10^3$ GeV, the nucleosynthesis upper bound requires that $m \lesssim 10^{12-13}$ GeV, which is less than would typically

²This estimate is based on a model with a single chiral superfield, so that the spin-1/2 components of the gravitino are effectively the inflatino [5]. It remains to be seen whether this remains true in more realistic models.

be expected in many inflation models, but which could nevertheless be satisfied with some moderately small couplings. For the case $T_R \approx 10^3$ GeV we have also calculated bounds for $T \approx 10^2$ GeV, corresponding to thermalization before the electroweak phase transition temperature, which is necessary for the existence of an electroweak phase transition. We see that this imposes quite a strong upper bound on the inflaton mass, $m_S \lesssim 10^{11}$ GeV. Finally, self-thermalization for $T_R \approx 10^3$ GeV requires that $m \lesssim 10^{10-11}$ GeV. For the case where T_R is of the order of the conventional thermal gravitino upper bound, $T_R \approx 10^8$ GeV, the nucleosynthesis bound requires that $m_S \lesssim 10^{16-17}$ GeV, which is easily (although not necessarily trivially) satisfied in inflation models such as D-term inflation. The electroweak transition bound requires that $m \lesssim 10^{14-15}$ GeV. Again, although this can be satisfied in many inflation models, it is nevertheless of the same order of magnitude as the inflaton mass expected in D-term inflation models, for example. Therefore it is non-trivial to have thermalization before the electroweak phase transition temperature, even in realistic inflation models with relatively high reheating temperatures! Finally, instantaneous reheating for $T_R \approx 10^8$ GeV occurs only if $m \lesssim 10^{12-13}$ GeV.

This shows that the assumption of a thermalized background following inflation, and in particular the existence of an electroweak phase transition, *strongly* depends upon the inflaton mass. In many inflation models it is likely that the relativistic particles of the radiation background will only thermalize at a relatively low temperature. Although for larger reheating temperatures it is quite easy to have thermalization before nucleosynthesis, it is not so clear that thermalization will occur before the epoch of the electroweak phase transition. For lower reheating temperatures, thermalization before nucleosynthesis can impose significant bounds on the inflaton mass and so on the model of inflation.

Finally, we comment on some assumptions made in this discussion. We have assumed throughout that the inflation decay products are massless. Of course, only the photons and possibly the gluons and neutrinos can be treated as massless throughout. However, this is sufficient for our discussion of thermalization, since once these particles thermalize they will serve as a thermalized background which can thermalize all

the other particles. In addition, we have also assumed that the only source of radiation is the single decaying inflaton field. In fact, shortly after the end of inflation, there may be other sources of radiation which could contribute to the thermalized seed leading to catalysed thermalization. This could provide a much larger number of seed particles, relaxing the upper bound from m_{seed} . For example, in D-term inflation models, in addition to the inflaton there are the fields $\psi_{+,-}$ responsible for hybrid inflation [6]. The rapid decay of the ψ_- field (which has a mass typically of the same magnitude as the inflaton mass [6, 10]) releases roughly the same energy in a time $\delta t \approx H_I^{-1}$ as that stored in the inflaton field at the end of inflation. Therefore the number of lowest energy particles in the spectrum, corresponding to those produced at $H \approx H_I$, is enhanced by a factor H_I/H_R . The result is that the m_{seed} upper bound is increased by a factor $(H_I/H_R)^{1/3}$, which is greater than 10^5 for $H_I \approx 10^{13}$ GeV and $T_R \lesssim 10^8$ GeV. In this case the upper bound from m_{cat} , which is unaffected, becomes the dominant bound on the inflaton mass.

4 Conclusions

We have considered the constraints following from the requirement that the relativistic decay products from inflaton decay thermalize. We have shown that the low energy decay products from inflaton decays occurring shortly after the end of inflation play a vital role in the thermalization of the whole energy spectrum, a process we refer to as catalysed thermalization. Requiring that the decay products do not thermalize before the temperature of the thermal gravitino upper bound allows the upper bound on the reheating temperature in SUSY inflation models to be increased from 10^8 GeV to 10^{10-12} GeV in realistic inflation models. Requiring that reheating occurs before to onset of nucleosynthesis can impose tight upper bounds on the inflation mass for low reheating temperatures, such as may be required by Affleck-Dine baryogenesis or non-thermal gravitino production. In addition, even in realistic inflation models with a relatively high reheating temperature, it is quite possible that the relativistic background will not thermalize before the temperature of the electroweak phase transition.

The lesson from all this is that the thermal history of the Universe after inflation is likely to be quite different from that naively assumed on the basis of instantaneous thermalization of the inflaton's decay products.

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